TIME- AND SPACE-RESOLVED TEMPERATURE MEASUREMENTS IN A COMBUSTION WAVE IN METHANE/AIR MIXTURES BY SPARK-EXCITED ROTATIONAL BANDS

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ABSTRACT

Measurements of the gas temperature in air and methane/air mixtures were made by analyzing a rotational band spectrum excited by a short spark. Time-resolved measurements were made in a afterglow spark plasma, and space- and time-resolved measurements across a propagating combustion wave. 107 µs after ignition one finds T_{max} = 1900 K and a flame front thickness of d = 0,3 mm.

1. INTRODUCTION

In a spark ignition engine fuel consumption and exhaust emission should be reduced in the future. For this the combustion and expansion process must be investigated exactly, in particular time- and space-resolved measurements of the temperature in the cylinder should be made for computer modelling of the combustion process by a two zone model as treated by Rauckis et al. /1/.

The new method which is used here for such temperature measurements is based on rotational band spectroscopy /2/. The rotational band used here is the 0-0 band of the 2nd positive group of the N_2 molecules, forming a band head at λ_h= 337,1 nm. Because the transition does not end at the ground state, there are no problems with absorption. The band is excited by a short spark which lasts no longer than a few ns.

The measurements yield the correct gas temperature, if rotation and translation of the molecules are in LTE and if the excitation happens in times which are so short, that no heating of the excited molecules takes place in this time by elastic collisions. This method can be used for gas temperature measurements as long as molecules exist, that means below T < 10000 K.

Up to now, resolved measurements of the temperature in motor cylinders were mostly made by the spectroscopical method of emission and absorption /3,4/. These measurements are limited to high temperatures (the gas has to emit radiation itself) and permits only a space resolution in the order of cm.

The method presented here enables high resolution in time (≈0,1µs) and space (≈0,1 mm), and does not need a self-emitting gas , so that measurements are even possible below room temperature.

2. EXPERIMENTAL

Fig. 1 shows schematically the experimental arrangement for measuring rotational bands, which are excited by a short spark. The detector for the band radiation is usually a photomultiplier (measurements with an optical multichannel analyser are under way). Therefore, because many measurements at different wavelengths are needed, the measurements have to be done in sampling technique.

The sample frequency is given by a pulse generator, which controls the main spark generator (DZ). The periodical main sparks generate a hot plasma, which inflames the gas in a small vessel, if this gas is a combustible mixture. The main spark duration is about $\tau = 60$ ns, its electrical energy about E = 30 mJ and its length d = 1 mm. Investigating a combustible mixture, the sample frequency is about $f_s = 1$ Hz. (This frequency is determined by the gas exchange frequency). Otherwise, investigating the main spark plasma itself e.g. in air, f_s can be increased to $f_s = 10$ Hz or more.

The unresolved radiation of the main spark is detected by the multiplier PM1 and its signal triggers the oscilloscope. After a defined delay the measuring spark generator (MSG) is triggered and generates the measuring spark. Its duration is about $5 < \tau \leq 10$ ns, its electrical energy about E = 200 µJ and its length d = 3 mm.

For measurements within a flame front the measuring spark is ignited perpendicularly to the main spark (and therefore perpendicular to the flame front too). A selectable part of the measuring spark radiation is focused on the entrance slit of the monochromator at a slit width of S = 0,1 mm. (Grating monochromator: Focus length 0,5 m, grating: 1200 lines/mm, reciprocal dispersion 1,6 nm/mm). The signal of PM2 is led to the sampling oscilloscope (aperture duration $\Delta\tau = 350$ ps). The trigger for this scope is delivered by the 2nd time base of the normal oscilloscope, which itself is triggered by the radiation of the measuring spark and which enters the PM1 too. The sampling oscilloscope is adjusted on maximum signal. The signal passes a low pass filter and is plotted as a function of the wave-length.

To find the correct temperature of the measured band spectrum, these spectra are compared with theoretical bands, which are calculated under convolution by the slit width of the monochromator.

An example of a calculated rotational band of N_2, Band 337,1 nm, is given in Fig. 2. The constants needed for calculating these bands can be found in /5/.

3. RESULTS

Analyzing the measuring spark band radiation in a gas of known temperature ($T = 300$ K).

The measuring spark has a duration of $\tau = 10$ ns. This spark is ignited periodically in N_2 at $p = 1{,}1$ bar and $T = 300$ K with $f_s = 10$ Hz. Its energy is $E = 300$ µJ and its length in this case $d_s = 2$ mm. Although the spark duration is only 10 ns, the band radiation can be measured - at decreasing intensity - in the spark afterglow up to $t_1 \approx 100$ ns after spark beginning. Here spark beginning is defined as that point which lies 25 ns before spark current maximum.

The rotational 337,1 nm bands measured at different times after spark beginning are given in Fig. 3. All temperatures obtained from the band spectra correspond to room temperature independent of t_1 delay times after spark beginning. This result is astonishing under consideration that the kernel of the spark reaches temperatures of about $T \approx 50000$ K approximately 30 ns after spark beginning /6/.

An answer to this ostensible discrepancy gives a measurement of the spark band radiation in radial resolution as reproduced in Fig. 4. The side on measured values of the band head radiation at $\lambda_h = 337{,}1$ nm, registrated with a radial resolution of $r = 25$um, are converted by Abel inversion to get the emission coefficient as a function of the radius in arbitrary units.

The profiles of the emission coefficient show that at later times the N_2 band radiation is emitted from the edge zones of the spark channel. Obviously these edge zones are not yet heated by the hot spark kernel so that the band radiation represents the low surrounding temperature. A further explanation of this behaviour is the possibility that the molecules in contact with the hot electrons are earlier dissociated than heated by elastic collisions.

Time-resolved temperature measurements in an afterglow spark plasma.

Further measurements were made in a decaying spark plasma. The plasma to be investigated was generated by a cable spark (duration $\tau = 12$ ns, energy $E = 300$ µJ, length $d = 1$ mm) in pure N_2 at $p = 1{,}1$ bar. In the same axial direction as this spark was fired, the measuring spark was generated too, delayed by either 2 µs or 50 µs respectively. At a delay of $t_1 = 2$ µs one finds a rotational temperature ot $T = 5300$ K. The rotational band belonging to this temperature is given in Fig. 5. The doublets of numbers in the spectrum indicate the transitions between the corresponding vibrational levels and the position in the spectrum indicates the place of the corresponding band head.

Fig. 6 shows an adequate measurement at $t_1 = 50$ µs after generating the spark plasma. The rotational temperature is about $T = 1200$ K.

Space- and time- resolved temperature measurements across a flame front (combustion wave).

These measurements were made in a small combustion chamber of $V = 5\ cm^3$. It is filled with a combustible methane/air mixture via a flame quenching inlet-pipe. The outlet-pipe is also of a flame quenching type. Therefore, if fresh mixture is continually flowing into the chamber - and an adequate burned fraction of the mixture out of it - the combustion can be ignited periodically without valves.

Fig.7 shows a sketch of the two sparks and the flame front. The measuring spark is ignited at $t_2 = 200\ \mu s$ after breakdown of the main spark. The flame front is about 2 mm away from the centre of the main spark. Within the burned mixture the measuring spark channel has a greater diameter than outside in the cold unburned gas (in the burned gas the gas density is smaller).

Because the plasma of the main spark and therefore the flame front too expand with a high velocity of $v \approx 2$ m/s, a lack of particles wants to arise in the centre of the plasma. But the pressure has to be equal within the chamber, and so cold gas flows axially into the centre. This can be seen in Fig. 8. Here is taken an interferogram at the same time ($t_2 = 200\ \mu s$) in axial direction of the main spark. Due to the flow in of the cold gas the hot burned gas or plasma forms a torus.

Fig. 9 shows a temperature profile measured at $t_2 = 107\ \mu s$ after ignition of the main spark. The methane/air mixture is stoichiometric and $p = 3{,}4$ bar. The measured maximum temperature is about $T \approx 1900$ K and the flame front thickness about $d \approx 0{,}3$ mm. In the centre due to the flowing in of cold gas the temperature is about $T \approx 900$ K. The flame front temperature and its thickness are comparable with those in the literature /7/.

For comparison a temperature profile of the spark plasma alone is also measured, however in air.

4. ACKNOWLEDGEMENT

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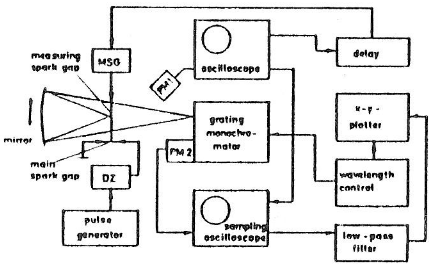

Fig.1 Experimental set-up for rotational band spectroscopy in sampling technique

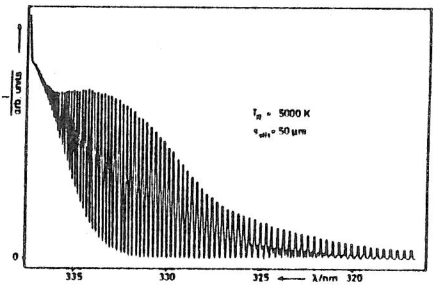

Fig.2 Theoretical N_2 0-0 band of the 2nd Pos. Group with λ_h=337,1 nm, convoluted with a slit width s_{slit}=50 µm

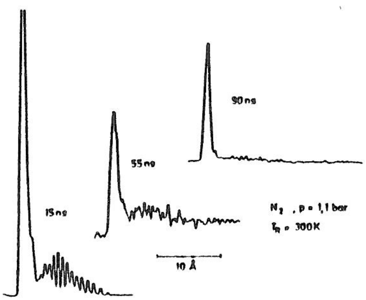

Fig.3 Measured 337,1 nm rotational bands at different times after spark beginning

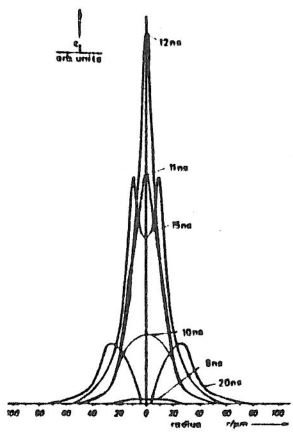

Fig.4 Emission coefficient ε_L of the band head radiation at λ_h=337,1 nm in radial resolution at different times after spark beginning

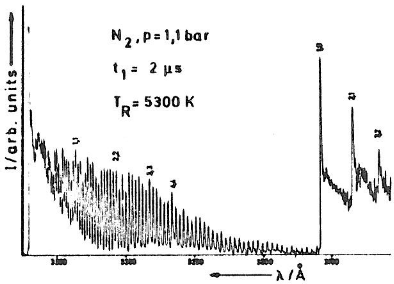

Fig.5 337,1 nm rotational band, excited t_1=2 µs after spark generation, measured in the afterglow

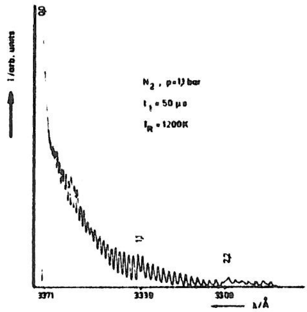

Fig.6 337,1 nm rotational band, excited t_1=50 µs after spark generation, measured in the afterglow

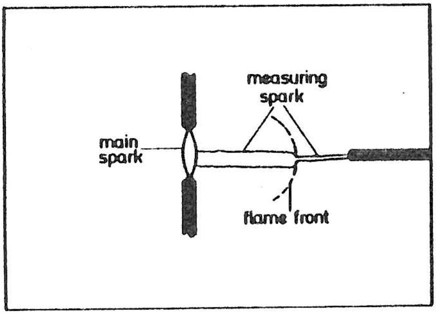

Fig.7 Sketch of the main and measuring spark, investigating a flame front t_2=200 µs after ignition of the main spark

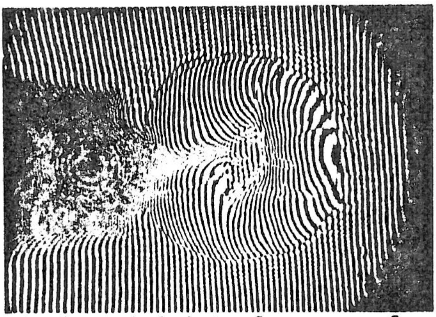

Fig.8 Axial interferogram of the burned region at t_2=200 µs after ignition of the main spark

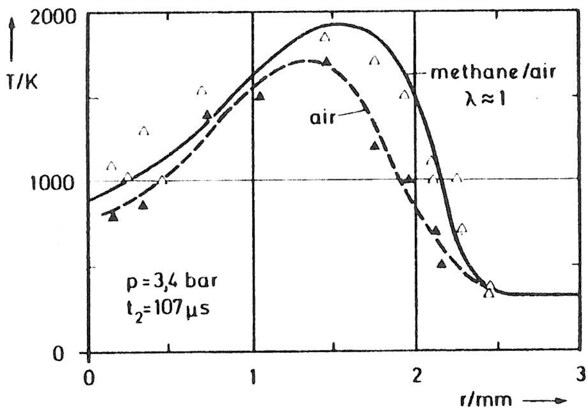

Fig.9 Radial temperature profile of a flame front, measured t_2=107 µs after ignition of the main spark. For comparison a temperature profile of the spark plasma alone is added.